Yield, Oil Content, and Composition of Sunflower Grown at Multiple Locations in Mississippi

Valtcho D. Zheljazkov,* Brady A. Vick, M. Wayne Ebelhar, Normie Buehring, Brian S. Baldwin, Tess Astatkie, and Jerry F. Miller

ABSTRACT

Sunflower (*Helianthus annuus* L.) is not a common crop in Mississippi and southeastern United States. There is potential for sunflower (for production of cooking oil or biodiesel) to fit into traditional cropping systems of Mississippi and to improve economic sustainability of agriculture in the region. The objective of the research was to evaluate the effect of N (0, 67, 134, and 202 kg ha^{-1}), hybrid (DKF3875, DKF2990, DKF3510, and DKF3901), and their interaction on seed yield, oil content, and oil composition of sunflower grown at five locations in Mississippi (Newton, Starkville, Stoneville, and two locations in Verona). Oleic acid concentration in the original planting seed oil was 29% (DKF3875), 26% (DKF2990), 85% (DKF3510), and 41% (DKF3901). In Stoneville, Newton, and Verona 2, DKF3510 had the highest seed yields. DKF2990 had lower yields in Stoneville and in Verona 2. Seed oil concentration was higher in DKF3875 and DKF2990 (43–47%) and lower in DKF3510 and DKF3901 (40–44%) at Stoneville and Verona 2. At Newton however, oil concentration was highest in DKF2990, lower in DKF3510 and DKF3901 and lowest in DKF3875. Overall, increasing N rates reduced seed oil concentration but increased seed yields and subsequently oil yield per area. Relative to the concentration in the original seed used for planting, oleic acid generally increased in all locations and hybrids. There was a corresponding decrease in the concentration of linoleic acid. Oil yields varied between 483 and 1388 L ha^{-1} and calculated biodiesel oil per area varied from 386 to 1110 L ha^{-1} with the different N treatments and locations. Sunflower can be a viable crop in most parts of Mississippi for production of cooking oil or biodiesel.

Research in North America has shown that sunflower can be successfully grown in the Midwest, northern states, and in Canada (Angadi and Entz, 2002a, 2002b; Johnston et al., 2002). The U.S. sunflower production is concentrated in North Dakota, South Dakota, Colorado, Kansas, Minnesota, Nebraska, and Texas (Johnston et al., 2002; NASS, 2006). Due to the well developed and deeply penetrating root system of this crop (Jaafar et al., 1993; Nielsen, 1998; Angadi and Entz, 2002a, 2002b; Stone et al., 2002), once established, sunflower is considered relatively drought tolerant (Robinson, 1978; Lindstrom et al., 1982; Stone et al., 2002) and uses soil nutrients efficiently (Connor and Hall, 1997; Valchovski, 2002). Hence, sunflower is usually grown in a rainfed system, and in some areas of the world (for example, Argentina), with no addition of fertilizers (Mercau et al., 2001; Ruiz and Maddonni, 2006).

V.D. Zheljazkov and N. Buehring, Mississippi State Univ., North Mississippi Research and Extension Center, 5421 Highway 145 South, P.O. Box 1690, Verona, MS 38879; B.A. Vick and J.F. Miller, Sunflower Research Unit, USDA-ARS, 1307 N 18TH ST, Northern Crop Science Lab., Fargo, ND 58105; W. Ebelhar, Delta Research and Extension Center, P.O. Box 197, Stoneville, MS 38776; B.S. Baldwin, Dep. of Plant and Soil Sci., Dorman Hall, Mississippi State Univ., MS 39762; T. Astatkie, Dep. of Engineering, Nova Scotia Agricultural College, 50 Pictou Road, P.O. Box 550, Truro NS B2N 5E3 Canada. Received 24 July 2007. *Corresponding author (vj40@pss.msstate.edu).

Published in Agron. J. 100:635–642 (2008).
doi:10.2134/agronj2007.0253

Sunflower oil has a wide range of applications, such as in the food industry, in commercial products, or in biodiesel production (Arkansas Biofuel Enterprises, 2007; National Sunflower Association, 2007). The fatty acid composition of vegetable oils influences their functional and nutritional properties (Warner et al., 2003; Burton et al., 2004) and determines their uses. The fatty acid composition of sunflower oil depends on genetic and environmental conditions (Robertson et al., 1978; Lajara et al., 1990; Miller and Vick, 1999; Sobrino et al., 2003). Sunflower seed contain up to 90% unsaturated fatty acids (combined oleic and linoleic), and approximately 10% saturated fatty acids (palmitic and stearic) (Steer and Seiler, 1990). Depending on fatty acid composition, sunflower can be divided into traditional sunflower with oleic acid content of 14 to 39% of the oil, mid-oleic acid sunflower (42–72% oleic acid content, also called NuSun, Mycogen, Breckenridge, MN, in the United States), and high-oleic acid sunflower (75–91% oleic acid) (Codex Alimentarius Committee, 2005). Consumers value mid-oleic and high-oleic acid sunflower because of their proven health benefits (Jing et al., 1997; Krajcovicova-Kudlackova et al., 1997; Hu et al., 2001). Hence, breeders have recently developed several mid- and high-oleic acid sunflower hybrids (Hardin, 1998; Kleingartner, 2002; Burton et al., 2004). Oleic acid and saturated fatty acids are desirable in frying, because unlike polyunsaturated fatty acids, they do not need to be hydrogenated. High- and mid-oleic sunflower oils are heart-healthy, with high stability in frying applications, and have a long shelf life, which makes the oil a valuable all-purpose commodity for the nearly 3 billion kg per year market of frying oils (Warner et al., 2003).

Abbreviations: ICAP, inductively coupled argon plasma spectrometer; LET, low energy technology; PPI, preplant incorporated.

Table 1. Selected initial soil characteristics (0–15 cm), the concentration of extractable nutrients in the soil from the five locations in Mississippi.

Location	Soil type	pH	OM†	P	K	Ca	Mg	Zn	S	Na
			%	kg ha^{-1}						
Newton	Prentiss fine sandy loam (coarse-loamy, siliceous, semiactive, thermic, Glossic Fragiudults)	6.9	0.87	132	147	1486	198	1.6	140	52
Starkville	Marietta fine sandy loam (fine-loamy, siliceous, active, thermic Fluvaguentic Eutrudepts)	5.0	1.17	145	88	560	39	4.1	168	97
Stoneville	Bosket very fine sandy loam (fine-loamy, mixed, active, thermic Mollic Hapludalfs)	5.1	1.11	192	599	2006	342	4.8	172	112
Verona 1	Catalpa silty clay loam (fine, montmorrillonitie, thermic, Fluvaguentic Halludolls)	7.1	1.81	120	278	4424	150	2.0	292	105
Verona 2	Quitman sandy loam (fine-loamy, siliceous, semiactive, thermic, Aquic Paleudult)	5.9	1.07	112	239	1923	115	1.8	176	76

† OM = Organic matter.

Although sunflower oil is known mainly as an edible oil for human nutrition, it can also be used for biodiesel production. Biodiesel is one of the renewable fuels that is produced mainly from soybean [*Glycine max*(L.) Merr.], canola (*Brassica* sp.), sunflower, and other oilseed crops (National Sunflower Association, 2007). According to the USDA, biodiesel offers environmental, economic, and national security benefits (National Sustainable Agriculture Information Service, 2007). With the acceptance of biodiesel as a replacement for petroleum-based fuel, growers in the southeastern United States have been looking for an opportunity to tap into this rapidly expanding market. The U.S. biodiesel demand increased by more than 400 times from 1999 to 2006 (National Sunflower Association, 2007). Most areas in Mississippi have spring-planted row crops, with significant expertise and equipment for growing the row crops. Sunflower has been shown to fit well into cereal-based rotations (Halvorson et al., 1999). Sunflower for biodiesel production was evaluated earlier in Florida within the low energy technology (LET) concept (Green et al., 1980, 1981, 1982) but has not been explored in Mississippi.

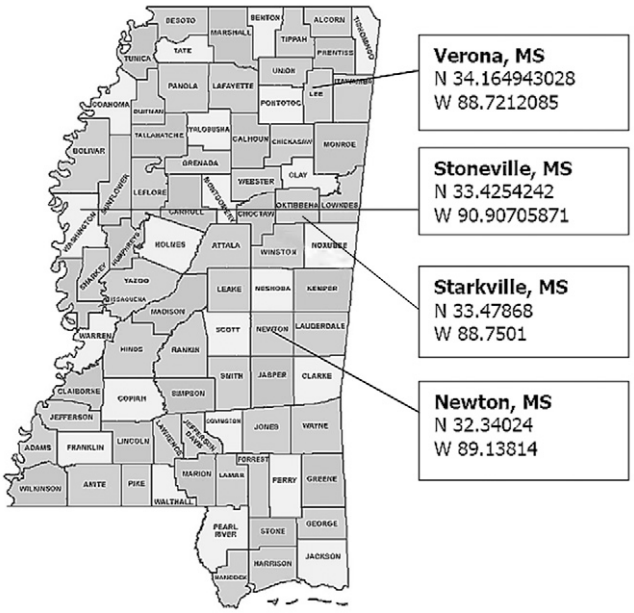

Fig. 1. Map of Mississippi with indication of the counties. The field experiments with the four sunflower hybrids were conducted at the Mississippi Agriculture and Forestry Experiment Stations (MAFES) research stations in Newton, Starkville, Stoneville, Verona 1, and Verona 2.

There is potential for sunflower (for production of cooking oil or biodiesel) to fit into some of the traditional cropping systems and subsequently to improve economic sustainability of agriculture in Mississippi. There is insufficient research on the effect of N and cultivar in the southern states with respect to productivity, oil content, and fatty acid profile of sunflower oil. No research on these characteristics has been reported for Mississippi conditions. Our hypothesis was that sunflower can be grown under Mississippi environmental conditions for cooking oil or biodiesel production, and both N rates and hybrids will have an effect on seed yield, oil content, and fatty acid composition. The objective of the research was to evaluate the effect of N, hybrid, and their interaction on yield, oil content, and composition of sunflower seed at five locations in Mississippi.

MATERIALS AND METHODS

Field Experiments

A field experiment was conducted during the 2006 cropping season at five locations in Mississippi (Newton, Starkville, Stoneville, and two locations in Verona) to evaluate the effect of hybrid (DKF3875, DKF2990, DKF3510, and DKF3901) and N application (0, 67, 134, and 202 kg ha^{-1}) on sunflower seed yield, oil content, and fatty acid composition. Certified seed of the four hybrids, produced in Woodland, CA, were provided by Monsanto Co., (St. Louis, MO). According to DeKalb (2007), DKF3875 is a traditional type; DKF2990 is traditional, downy mildew resistant; DKF3510 is mid-oleic acid (NuSun), downy mildew resistant; and DKF3901 is traditional, downy mildew resistant (DeKalb, 2007).

The fatty acid composition of the seed oil of the four hybrids resulted from the influence of both the hybrid genotype and the environment of the hybrid seed production fields in Woodland, CA. Five locations (Fig. 1) were chosen to represent major growing areas and different soil types of Mississippi (Table 1). All five sites had different soil types (Table 1) (U.S. Department of Agriculture, Soil Survey Division, Natural Resources Conservation Services, 2001).

Nutrient Analyses of Soil

Soil samples were taken before seeding at the five locations. Air-dried and ground soil samples were extracted using the Lancaster soil test method (Cox, 2001) at the Mississippi State University Soil Testing and Plant Analyses Laboratory. Concentrations of nutrients in soil were measured by an induc-

tively coupled argon plasma spectrometer (ICAP) (Thermo Jarrell Ash, Franklin, MA). Phosphorus and K fertilizers were broadcast and incorporated in accordance with soil analyses and recommendations at each location. The fertility additions were designed to provide understanding of sunflower yield response to a range of N rates without limiting effects of P or K.

The previous crop at each of the five locations was different: fallow in Newton, corn in Stoneville and Verona 1, soybean in Starkville, and perennial grass in Verona 2 locations. Soil tillage was as traditional for row crops in the region and included disking and formation of raised beds at 97 to 102 cm center to center at the beginning of April. The raised beds are typically used for row crops in the region to improve surface drainage. Weed control at all locations was conducted by using preplant incorporated (PPI) herbicide Treflan (DowAgroSciences, Zionsville, IN; trifluralin: α,α,α-trifluoro-2,6-dinitro-*N*,*N*-dipropyl-*p*-toluidine) at 4.5 to 5.6 kg ha^{-1}, depending on soil type. The herbicide was applied after the initial formation of the raised beds, and then carefully incorporated. Seeding was accomplished with a cone planter at 3.8 cm depth, at 97 to 102 cm interrow space, and a seeding rate to provide 6.4 seed m^{-1} of row. Because of differences in seed size among the hybrids, seeding rate (by weight) was different for each hybrid, but was the same for a particular hybrid at every location. Seeding rates for the hybrids DKF2990, DKF3510, DKF3875, and DKF3901 were 3.47, 5.12, 4.37, and 4.13 kg ha^{-1}, respectively. Plots were 6 by 4 m, with four rows in every plot.

Nitrogen [as urea-ammonium nitrate solution (UAN) 32% N] was knifed in on either side of the row (20–25 cm from row) and was applied in 67 kg ha^{-1} increments: the first 67 kg increment in the 67, 134, and 202 kg ha^{-1} N treatments was applied at the seeding stage; the second application (in the 134 and 202 kg ha^{-1} N treatment) was applied a month later in V-4, R-1 stage (Schneiter and Miller, 1981), and a third application (in the 202 kg ha^{-1} treatments) a month later after the second application in R-2 stage (Schneiter and Miller, 1981). With respect to diseases, head rot (*Rhizopus* sp.) was identified; however, the incidence was very low and did not warrant any treatments. Blackbirds (*Agelaius phoeniceus* L.) proved to be a major pest factor. For control of blackbirds, propane cannons were used. Also, stem weevil (*Cylindrocopturus adspersus* LeConte) and head clipping weevil (*Haplorhynchites aeneus* Boh.) infestation was found at the two Verona locations only. Hence, sunflower at Verona was treated with Sevin (80% carbaryl, Lesco, Inc., Tjroy, MI) at 1.4 kg ha^{-1}. Harvesting commenced when all plants reached harvesting maturity, after physiological stage R-9 (Schneiter and Miller, 1981), and was accomplished by harvesting the two inner rows in each plot. Threshing was done using a stationary thresher (Almaco, LPR-E, Nevada, IA), seed moisture was determined using a stationary electronic grain-moisture tester (Model GAC2000, Dickey-John, Auburn, IL) in a 500-g sample from each plot. Seed subsamples (around 100 g) from each plot at the five locations were further cleaned by hand to remove any occasional broken seed or impurities, put immediately in a freezer at –20°C for 24 h to prevent disease development and kill insects, and then stored in a refrigerator at 4°C until further analysis.

Fatty Acid Composition Analysis

Each sample of clean and unbroken seed was ground in a Krupps coffee grinder and a portion (0.15–0.25 g) was added to a 13 × 100 mm disposable culture tube. Three milliliters of a solution of hexane-chloroform-0.5 *M* sodium methoxide in methanol (Sigma, St. Louis, MO) (75:20:5, v/v/v) was added to the tube and the mixture was vortexed for 2 to 5 s. The mixture was settled for 10 min and the upper clear portion was transferred to a vial. The vial was capped and the sample was injected into a Hewlett-Packard Model 5890 gas chromatograph containing a DB-23 capillary column (30 m × 0.25 mm, J&W Scientific, Folsom, CA), which was held at 190°C for 4 min, then increased to 220°C at 15°C/min, held at 220°C for 1 min, then increased to 240°C at 25°C/min, and finally held at 240°C for 1.0 min, for a total run time of 8.8 min. Fatty acid concentrations are expressed as percent by weight of the total fatty acids.

Oil Content Analysis

Oil content of the seed was determined using a 40-mL sample of cleaned, weighed seed using a Maran Ultra Resonance NMR instrument (Resonance Instruments Ltd., Witney, UK), following the American Oil Chemists' Society Official Methods and Recommended Practices, AK4–95 (American Oil Chemists' Society, 1994). Because seeds from different hybrids had various moisture contents, oil contents were adjusted to 0% moisture content.

Statistical Methods

For each of the five locations, the design was two-factor factorial in four blocks for yield response, and in three blocks for the fatty acid composition responses. The factors of interest: hybrid with four levels (DKF3875, DKF2990, DKF3510, and DKF3901) and N application rate with four levels (0, 67, 134, and 202 kg ha^{-1}) were treated as fixed. Block effect was treated as random in the Mixed procedure of SAS (SAS Institute Inc., 1999). Since the fatty acid compositions for the different hybrids of the original certified seed were not uniform (Table 2), the corrected fatty acid composition responses calculated as the difference between the measured and the original were analyzed. The implication of this correction is: if a treatment mean is positive, then the treatment increases the composition; and if it is negative, then the treatment decreases the composition. For each response and within each location, the residuals were exam-

Table 2. Mean fatty acid concentration of the original certified seed of the four sunflower hybrids. The analysis of variance and subsequent results in the following tables are based on the response measurements minus these values to correct for the differences among the hybrids.

Hybrid	Palmitic	Stearic	Oleic	Linoleic
	Mean, in % of the oil			
DKF3875	6.59	4.03	28.56	58.53
DKF2990	6.12	5.12	26.14	59.68
DKF3510	4.16	4.25	85.04	4.29
DKF3901	6.25	5.31	41.73	44.30
	Coefficient of Variation, %			
DKF3875	1.15	2.59	0.80	0.41
DKF2990	1.36	0.90	1.96	0.57
DKF3510	0.42	0.62	0.82	12.23
DKF3901	0.88	1.10	2.34	1.86

ined to verify normal distribution and constant variance assumption of the error terms as described in Montgomery (2005).

Multiple means comparison was completed for marginally significant (*P* value between 0.05 and 0.1) and significant (*P* value <0.05) effects. For the responses with significant or marginally significant interaction between hybrid and N rate, the Least Squares means of all 16 hybrid by N rate combinations were compared using the lsmeans statement of Proc Mixed with pdiff option to produce *P* values for all pairwise differences, and then letter groupings generated using 0.01 level of significance to protect Type I experimentwise error rate from overinflation. However, for the responses with nonsignificant interaction effect, but with a significant main effect, the Least Squares means of the four levels were compared and letter groupings generated in the same way using a 0.05 level of significance.

RESULTS AND DISCUSSION

Fatty Acid Composition of the Original Seed Used in this Study

The composition of fatty acids in the original seed differed among the four hybrids (Table 2). DKF3510 can be characterized as a high-oleic sunflower, DKF3875 and DKF2990 belong to the traditional class of sunflower with high polyunsaturated fatty acid (linoleic), while DKF3901 is a mid-oleic acid sunflower, intermediate in both oleic and linoleic acid compared to the high/low values in other hybrids (Canadian Food Inspection Agency, 2007; Codex Alimentarius Committee, 2005). If the classification of the National Sunflower Association (www.sunflowernsa.org) is followed, DKF3875, DKF2990, and DKF3901 would be considered traditional, whereas DKF3510 would be high-oleic acid sunflower oil (National Sunflower Association, 2007). Also, DKF3510 had a lower than 10% concentration of saturated fatty acids (palmitic plus stearic), while the combined concentration of palmitic and stearic acids of the other hybrids was >10% of the oil.

Main and Interaction Effects of Hybrid and Nitrogen on Measured Responses

Statistical analyses indicated that the interaction effect of hybrid and N rate was significant on seed yield at the Verona 1 and Starkville (marginally) locations suggesting that at these locations, effectiveness of N application depends on the hybrid (Table 3). At the Stoneville, Newton (marginally), and Verona 2 (marginally) locations, the main effect of hybrid was significant on yields, whereas the main effect of N rate was significant at Stoneville only (Table 3).

There was significant interaction effect of hybrid and N rate on the concentration of palmitic acid at the Stoneville, Starkville, and the two Verona locations, while hybrid significantly affected this acid only at the Newton location. Regarding stearic acid concentration, the main effects of both hybrid and N rate were significant at the Stoneville, Newton, and Verona 2 locations. The main effect of hybrid was significant at Starkville, and there was a significant interaction effect between hybrid and N rate at the Verona 1 location (Table 3).

Concentration of one of the main fatty acids, oleic, was significantly affected by hybrid at all locations. In addition, oleic acid was marginally affected by N rate at the Verona 2 location. With the exception of the Verona 2 location (where there was a marginally significant interaction between hybrid and N rate), hybrid was the major modifier of linoleic acid, the other major acid in sunflower oil (Table 3).

Hybrid and N rate were significant with respect to oil concentration (corrected for 0% seed moisture) at Stoneville, Newton, and the Verona 2 location, but only the main effect of hybrid was significant on oil content at the Verona 1 location (Table 3). These results confirm the general understanding that both genotype and environment are major modifiers of seed oil content of sunflower (Leon et al., 2003).

Effect of Hybrid on Seed Yields in Different Locations

At Stoneville, DKF3510 provided higher seed yields compared to DKF3901 or DKF2990 (Table 4). However, DKF3875 yielded similarly to DKF3510 and to DKF3901. At

Table 3. ANOVA *P* values for the main and interaction effects of Hybrid (H) and N rate (R) on seed yield; and the corrected values of palmitic, stearic, oleic, and linoleic fatty acid compositions; and uncorrected Oil0 (% seed oil content calculated for 0% seed moisture) from the four sunflower hybrids grown at four different N rates at five locations in Mississippi.

Location	SV	Seed yield	Palmitic	Stearic	Oleic	Linoleic	Oil0
Stoneville	H	**0.001**†	0.001	**0.001**	**0.001**	**0.001**	**0.001**
Stoneville	R	**0.018**	0.294	**0.001**	0.799	0.676	**0.001**
Stoneville	H × R	0.872	**0.013**	0.285	0.531	0.495	0.504
Newton	H	**0.079**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
Newton	R	0.466	0.306	**0.023**	0.472	0.327	**0.001**
Newton	H × R	0.269	0.548	0.486	0.561	0.317	0.105
Starkville	H	0.003	0.001	**0.001**	**0.001**	**0.001**	0.304
Starkville	R	0.020	0.172	0.100	0.289	0.213	0.111
Starkville	H × R	**0.054**	**0.038**	0.617	0.149	0.115	0.818
Verona 1	H	0.239	0.001	0.001	**0.001**	**0.001**	**0.001**
Verona 1	R	0.001	0.658	0.009	0.825	0.848	0.166
Verona 1	H × R	**0.015**	**0.049**	**0.012**	0.162	0.213	0.318
Verona 2	H	**0.086**	0.001	**0.001**	**0.001**	0.001	**0.010**
Verona 2	R	0.199	0.035	**0.001**	**0.064**	0.036	**0.001**
Verona 2	H × R	0.613	**0.023**	0.541	0.119	**0.080**	0.674

† Values in bold indicate significant or marginally significant effects that needed multiple means comparison.

Table 4. Least squares means together with letter groupings of seed yield; the corrected values of palmaitic, stearic, oleic, and linoleic fatty acid compositions; and uncorrected Oil0 (% seed oil content calculated for 0% seed moisture) for the four hybrids grown at five locations in Mississippi.

Location	Hybrid	Seed yield	Palmitic	Stearic	Oleic	Linoleic	Oil0
		kg ha^{-1}			%		
Starkville	DKF3875			–0.78 a†	19.7 a	–17.5 c	47.2 a
Starkville	DKF2990	Fig. 2‡	Fig. 3	–2.15 d	20.9 a	–18.1 c	47.9 a
Starkville	DKF3510			–1.49 c	1.8 c	–0.5 a	46.0 a
Starkville	DKF3901			–1.18 b	12.2 b	–10.5 b	46.1 a
Stoneville	DKF3875	2767 ab		–1.01 a	27.0 b	–24.2 c	45.6 a
Stoneville	DKF2990	2304 c	Fig. 3	–2.20 c	32.4 a	–28.8 d	46.4 a
Stoneville	DKF3510	2972 a		–1.53 b	0.5 d	0.8 a	43.6 b
Stoneville	DKF3901	2652 b		–1.63 b	17.2 c	–14.8 b	44.1 b
Newton	DKF3875	1385 b	–1.33 d	–0.15 a	11.0 b	–11.9 b	39.2 c
Newton	DKF2990	1428 ab	–0.96 c	–2.06 c	23.1 a	–21.3 c	43.5 a
Newton	DKF3510	1551 a	–0.25 a	–1.08 b	0.9 c	–0.3 a	41.9 b
Newton	DKF3901	1349 b	–0.67 b	–0.96 b	1.9 c	– 2.5 a	41.7 b
Verona 1	DKF3875				16.4 b	–14.9 c	51.2 b
Verona 1	DKF2990	Fig. 2	Fig. 3	Fig. 4	28.2 a	–24.6 d	52.3 a
Verona 1	DKF3510				2.8 d	–0.6 a	48.3 d
Verona 1	DKF3901				9.3 c	–7.4 b	49.6 c
Verona 2	DKF3875	1122 ab		–0.78 a	19.8 b		43.1 a
Verona 2	DKF2990	922 b	Fig. 3	–2.15 d	24.2 a	Fig. 4	42.5 a
Verona 2	DKF3510	1107 ab		–1.49 c	–0.1 d		40.5 b
Verona 2	DKF3901	1220 a		–1.18 b	8.7 c		40.4 b

† Within each location, means followed by the same letter are not significantly different at the 0.05 level.

‡ A figure number indicates that the interaction between Hybrid and N Rate was significant, and that the multiple means comparison results are shown in figures.

Newton, higher yields were provided by DKF3510 with lower yields from DKF3901 and DKF3875, whereas yields from DKF2990 were not different from the other hybrids. At the Verona 2 location, DKF3901 provided greater yields compared to DKF2990, while yields from the other two hybrids were not significantly different from DKF3901 or DKF2990. The above results suggest that genotypes (hybrids) can express differential comparative productivity depending on the local environment conditions and soil properties (Table 1).

Effect of Hybrid on Fatty Acid Composition and Seed Oil Content

Stearic and Palmitic Acid

Overall, the concentration of stearic acid in sunflower grown at the Stoneville, Newton, Starkville, and Verona 2 locations tended to be lower relative to the respective concentration in the original seed (Table 4 and Table 2). DKF3875 provided the lowest reduction at all locations. Palmitic acid in all hybrids at Newton decreased relative to the original seed. In general, reduction of saturated fatty acids (such as stearic) is desirable by consumers, although stearic acid is preferred over other saturated acids because it may not increase cholesterol (Pierson, 1994).

Oleic Acid

With the exception of one hybrid at one location (DKF3510 at the Verona 2 location), the concentration of oleic acid in all hybrids at all five locations increased relative to the oleic acid concentration in the original certified seed (Table 4 and Table 2). This increase in oleic acid actually "transformed" traditional sunflower hybrids DKF3875, DKF2990, and DKF3901 into mid-oleic acid sunflower (Codex Alimentarius Committee, 2005) or even into NuSun (National Sunflower Association, 2007), which is a significant finding. Overall, the increase in oleic acid concentration relative to the original seed depended on the hybrid: the lower the oleic acid concentration in the original seed, the higher was the increase for oleic acid concentration. Hence, a higher increase in oleic acid was found in DKF2990, lower in DKF3875, even lower in DKF3901 and lowest in DKF3510.

Linoleic Acid

Overall, the linoleic acid decreased relative to the respective concentrations in the original seed (Table 4 and Table 2). However, this reduction depended on hybrid; and at all locations, whenever there was an increase in the oleic acid concentration, there was a corresponding decrease in linoleic acid concentration.

Our results indicate that genotype (hybrid) determined the concentration of the main fatty acids in sunflower oil, oleic and linoleic. Indeed, previous research demonstrated that the fatty acid profile of sunflower oil is genetically controlled (Burton et al., 2004). In general, our results also support earlier studies that found a strong influence of environmental conditions on oil profile (Robertson et al., 1978). However, this is the first study to demonstrate such a dramatic increase in oleic acid content of sunflowers relative to the original seed.

Seed Oil

Seed oil concentration in this study was generally high and similar to previous reports (de la Vega and Hall, 2002,; National Sunflower Assocation, 2007). Seed oil concentration is important for growers and processors. For example, currently, sunflower crushing plants in North Dakota and in Kansas offer 2% price premium for every 1% oil above 40% (National Sunflower Assocation, 2007). At the Stoneville and Verona 2 locations, DKF2990 and DKF3875 contained a greater amount of oil compared to the other two hybrids (Table 4). However, at Newton, oil content was higher in DKF2990, less in DKF3510 and DKF3901, and least in DKF3875. Oil content at Verona 1 was highest in DKF2990, less in DKF3875, lower in DKF3901 and lowest in DKF3510 (Table 4). The above results suggest that sunflower seed oil concentration depends on genotype (hybrid), but it may be expressed differentially under different environments.

Effect of N on Seed Yields, Oil Content, and Fatty Acid Composition

At Stoneville, seed yields were increased with increased N rates at 67 to 202 kg ha^{-1} (Table 5). At Stoneville, Newton, and Verona 2 locations, increasing N rates tended to decrease the reduction in the concentration of stearic acid relative to the original seed (Table 5). However, the reduction was not significantly different for 67 to 202 kg ha^{-1} N rates. Unlike at

Table 5. Least squares means together with letter groupings of yield (kg ha^{-1}), and the corrected values of stearic and oleic fatty acid compositions and uncorrected Oil0 (% seed oil content calculated for 0% seed moisture) for the four N rates at Stoneville, Newton, and Verona 2 locations in Mississippi.

Location	N rate	Yield	Stearic	Oleic	Oil0
	kg ha^{-1}		%		
Stoneville	0	2435 b†	–1.78 b		46.9 a
Stoneville	67	2 835 a	–1.60 a		44.8 b
Stoneville	134	2682 ab	–1.48 a		44.0 b
Stoneville	202	2743 a	–1.51 a		43.9 b
Newton	0		–1.24 b		43.1 a
Newton	67		–1.07 ab		42.5 a
Newton	134		–1.01 a		40.5 b
Newton	202		–0.92 a		40.4 b
Verona 2	0		–1.82 c	11.1 b	48.1 a
Verona 2	67		–1.50 b	12.2 ab	46.2 b
Verona 2	134		–1.22 a	13.9 ab	43.7 c
Verona 2	202		–1.21 a	15.4 a	44.4 c

† Within each location, means followed by the same letter are not significantly different at the 0.05 level.

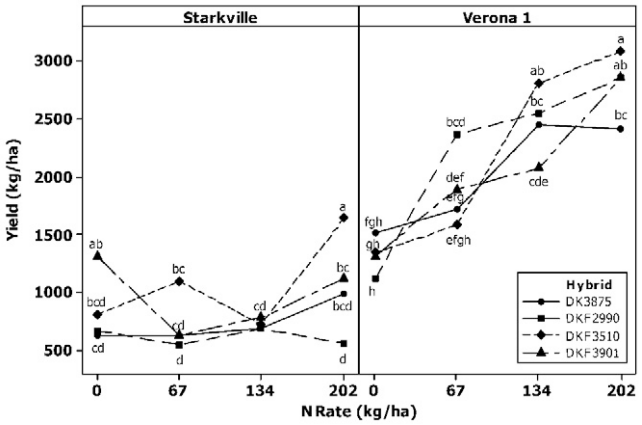

Fig. 2. Interaction plot of mean yield versus N rate for the four hybrids at the Starkville and Verona 1 locations. Within each location, means sharing the same letter are not significantly different at the 0.01 level of significance.

the other locations, the application of N at a higher rate significantly increased oleic acid at the Verona 2 location.

In general, results from the three locations (Stoneville, Newton, and Verona 2) suggest that higher N rates may decrease the oil content in seed (Table 5). However, because of the higher yields, oil yields per area were greater with higher N rates (data not shown). Oil yield (calculated from seed yields and oil content) varied between 406 and 1166 kg ha^{-1} (483 and 1388 L ha^{-1}) for different N treatments (data not shown). Calculated biodiesel oil per area (calculated from the oil yield multiplied by 0.8) ranged from 386 to 1110 L ha^{-1} (41–119 gallon/acre). The calculated biodiesel oil in this study is similar to values reported by others (Halvorson et al., 1999; Arkansas Biofuel Enterprises, 2007; National Sunflower Association, 2007), suggesting sunflower may be a viable crop for biodiesel production in Mississippi.

The above results suggest that genotypes react differently to the environmental conditions in different areas of Mississippi with respect to oleic and linoleic acid concentration, and fatty acid composition in general. Sunflowers grown in Mississippi would generally increase the accumulation of oleic acid of traditional sunflower and "transform" them into mid-oleic acid or NuSun hybrids (National Sunflower Association, 2007). This may improve marketability of sunflower seed oil produced in Mississippi because consumers value high-oleic acid sunflower seed. Reducing the concentration of saturated fatty acids in vegetable oils is preferred by consumers and has promoted breeding programs for low stearic and palmitic acid sunflower (Burton et al., 2004; Miller and Vick, 1999). As expected, the increase in oleic acid causes a corresponding reduction in the accumulation of linoleic acid in sunflower oil. The increase in oleic acid from north to south latitude and the corresponding reverse trend in linoleic acid has been reported by Robertson et al. (1978). The same authors found that latitude had limited effect on saturated fatty acid concentration in sunflower oil. Similar results on the effect of climatic conditions and latitude on linoleic acid were reported by Lajara et al. (1990). Sobrino et al. (2003) developed models to explain and predict oleic acid concentration in sunflower oil as a function of geographic and climatic conditions. They reported temperature during development and maturation of sunflower achenes is one of the most important factors for production of oleic acid. Izquierdo et al. (2006) also developed a model for predicting fatty acid composition in sunflower. They found that during the 100 to 300 degree-days (above 6°C) after flowering, the minimum night temperatures accounted for most of the variability of oleic acid concentration.

Interaction Plots

Interaction plots of hybrid by N application rate revealed that at the Starkville location, N rates at 202 kg ha^{-1} increased yields from DKF3510, but did not affect yields for DKF3875 or DKF2990 (Fig. 2). Nitrogen at 67 and 134 kg ha^{-1} rates decreased yields of DKF3901. Yields at 202 kg ha^{-1} increased relative to the 67 kg ha^{-1} N rate, but were not different from the 0 kg ha^{-1} or the 134 kg ha^{-1} rates. At the Verona 1 location, N application in general increased yields in all hybrids (Fig. 2). Yields from DKF3875 and DKF3510 increased correspondingly in the 67 rate and then in the 134 kg ha^{-1} N rates, but further N increase did not result in a corresponding yield increase. For DKF2990, higher yields were achieved in the 67 kg ha^{-1} rate, but further N increase did not bring a corresponding yield increase. It has been demonstrated that sunflower is a good N scavenger and may require relatively low N fertilizer application rates (34 kg N ha^{-1}) to provide good yields (Halvorson et al., 1999). Hence, in some countries sunflower is grown with no addition of fertilizers (Mercau et al., 2001; Ruiz and Maddonni, 2006). Seed yields at the Verona 1 location were high and similar to sunflower yields reported in the literature (Halvorson et al., 1999; de la Vega and Hall, 2002). Overall, seed yields in this study at four of the locations were similar or much exceeded the average sunflower yields in the United States for the 2001–2006 period, which varied between 1280 and 1750 kg ha^{-1} (National Sunflower Association, 2007).

At Stoneville, N at 134 and 202 kg ha^{-1} increased the concentration of palmitic acid in DKF3901, but not in other hybrids (Fig. 3). At Starkville, increased N rates did not change palmitic acid concentration in oil (Fig. 3). At the Verona 1 location, N rates at 134 and 202 kg ha^{-1} increased palmitic acid in the oil of DKF3875, and N rate at 202 decreased palmitic acid in DKF2990 relative to the 0 kg N ha^{-1}. However, at the Verona 2 location, N rates at 134 and 202 kg ha^{-1} decreased palmitic acid in the

oil of DKF3875 relative to the 0 kg N ha^{-1}. Also in DKF2990, N at 202 kg ha^{-1} decreased palmitic acid relative to the 0 kg N ha^{-1} treatment (Fig. 3).

At the Verona 1 location, N at 202 kg ha^{-1} reduced stearic acid in DKF3875 relative to the 0 kg N ha^{-1} and the 67 kg N ha^{-1} rates (Fig. 4). Nitrogen at 67 and 134, but not at 202 kg N ha^{-1} rate, reduced stearic acid in DKF3901. Furthermore, N at 67 kg ha^{-1} decreased stearic acid in DKF2990 relative to the 0 kg ha^{-1} rates. At the Verona 2 location, N at 134 and 202 kg ha^{-1} rates reduced linoleic acid in DKF3875 and DKF2990 relative to the respective 0 kg ha^{-1} N rate (Fig. 4).

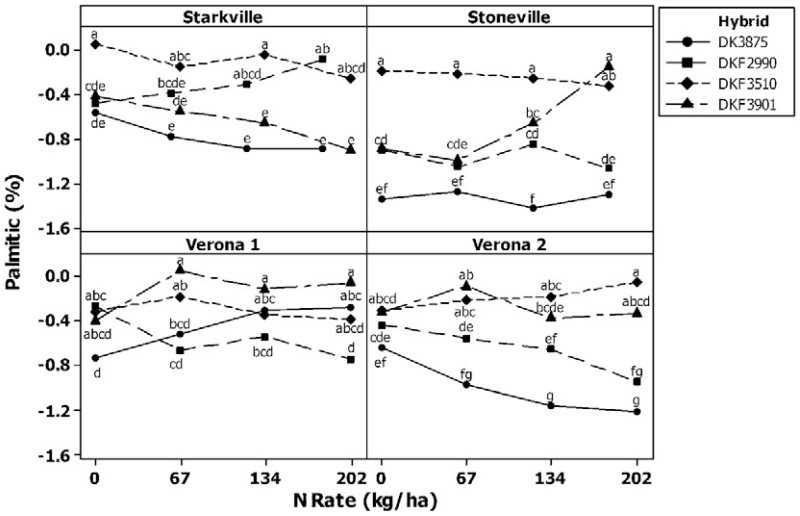

Fig. 3. Interaction plot of mean corrected palmitic (%) vs. N rate for the four hybrids at the Stoneville, Starkville, Verona 1, and Verona 2 locations. Within each location, means sharing the same letter are not significantly different at the 0.01 level of significance.

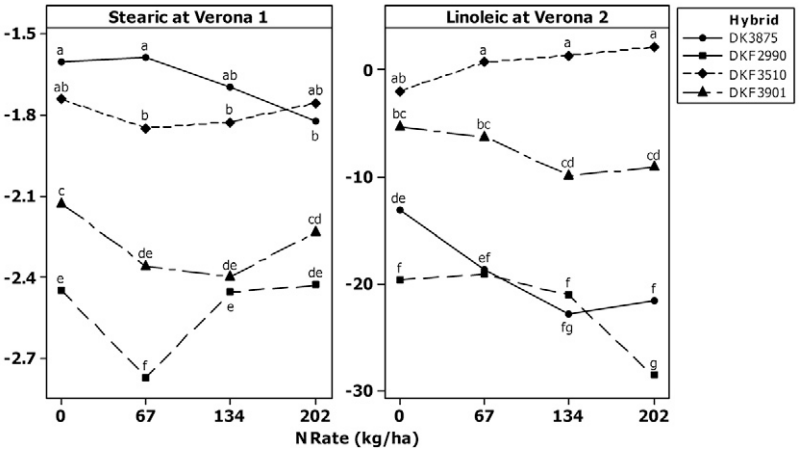

Fig. 4. Interaction plot of mean corrected stearic (%) at the Verona 1 location and linoleic (%) at the Verona 2 location vs. N rate for the four hybrids. Within each location, means sharing the same letter are not significantly different at the 0.01 level of significance.

CONCLUSION

Overall, this study demonstrated sunflower could be a viable crop in Mississippi with yields comparable to other regions of the United States. Generally, increasing N rates reduced seed oil concentration but increased seed yields and subsequently oil yield per area. In most cases, N rate, hybrid, or N by hybrid interaction resulted in altered fatty acid profile of sunflower oil compared to the composition of the planted seed, with the effects being different at the different locations. Overall, fatty acid composition depended mainly on genotype (hybrid). Increased N application rates increased oleic acid concentration of the four hybrids in the Verona 2 location and decreased stearic acid concentration in the Stoneville, Newton, and Verona 2 locations.

The increase in oleic acid content in sunflower grown in Mississippi (relative to the original seed) could be used as a marketing tool, because oleic acid has been shown to have nutritional benefits and to reduce coronary heart disease (Jing et al., 1997; Krajcovicova-Kudlackova et al., 1997; Hu et al., 2001). The U.S. Department of Agriculture dietary recommendations call for a reduction of saturated fatty acids by the American consumer (U.S. Department of Agriculture, Human Nutrition Information Service, 1992). Also, high-oleic acid sunflower oil does not need to be hydrogenated when used as a frying oil, which offers significant advantages over the use of other vegetable oils such as soybean, canola, and traditional low-oleic acid sunflower (Kleingartner, 2002; National Sunflower Association, 2007). Although linoleic acid is valuable for the paint industry and has also been recognized to have health benefits, it may be less important than high-oleic acid, since other less expensive vegetable oils [soybean and corn (*Zea mays* L.)] are also high in linoleic acid and have an established status on the American market (Kleingartner, 2002). Hence, the high-oleic acid of sunflower oil translates into improved health and frying advantages. Our preliminary data demonstrated that sunflower production in Mississippi and possibly in other southern states is feasible. Sunflower could be grown as an oilseed or biodiesel crop in Mississippi and possibly for the health market. Further research is needed to establish the best management practices for sunflower in Mississippi and to evaluate sunflower in rotation with other field crops in the region.

ACKNOWLEDGMENTS

Authors acknowledge the financial support by the Department of Energy for the project Feedstocks for Sustainable Energy Systems in Mississippi. Authors thank Mr. Billy Johnson, Mr. Thomas Horgan, Mrs. Marie Rogers, Mr. Scott Horton, Mr. Robert Dobbs, Mr. Davis Clark, and Mr. Mark Harrison for their help in the field and laboratory. Contribution of the Mississippi Agricultural and Forestry Experiment Station journal article no. J-11260.

REFERENCES

Angadi, S.V., and M.H. Entz. 2002a. Root system and water use patterns of different height sunflower cultivars. Agron. J. 94:136–145.

Angadi, S.V., and M.H. Entz. 2002b. Water relations of standard height and dwarf sunflower cultivars. Crop Sci. 42:152–159.

American Oil Chemists' Society. 1994. Official methods and recommended practices of American Oil Chemists' Society. 4th ed. Am. Oil Chem. Soc. Press, Champaign, IL.

Arkansas Biofuel Enterprises. 2007. Crop yields in gallons. Available at http://home.earthlink.net/~arkansasbiofuels/id33.html (accessed April 2007; verified 7 Mar. 2008).

Burton, J.W., J.F. Miller, B.A. Vick, R. Scarth, and C.C. Holbrook. 2004. Altering fatty acid composition in oil seed crops. Adv. Agron. 84:273–306.

Canadian Food Inspection Agency. 2007. Decisions: Fats, oils and fatty acids. Available at http://www.inspection.gc.ca/english/fssa/labeti/decisions/fatgrae.shtml (verified 7 Mar. 2008).

Codex Alimentarius Committee. 2005. Codex standard for named vegetable oils. Codex-Stan 210, p. 2. Available at http://www.codexalimentarius.net/web/standard_list.do?lang=en (verified 7 Mar. 2008).

Connor, D.J., and A.J. Hall. 1997. Sunflower physiology. p. 113–182. *In* A.A. Schneiter (ed.) Sunflower technology and production, Agron. Ser. 35. ASA, Madison, WI.

Cox, M.S. 2001. The Lancaster soil test method as an alternative to the Mehlich 3 soil test method. Soil Sci. 166:484–489.

DeKalb. 2007. Available at http://www.asgrowanddekalb.com/seedresourceguide/product/SUNFLOWER/DKF39-01.pdf (accessed July 2007; verified 7 Mar. 2008).

De la Vega, A.J., and A.J. Hall. 2002. Effect of planting date, genotype, and their interactions on sunflower yield: II. Components of oil yield. Crop Sci. 42:1202–1210.

Green, V.E., Jr., J.A. Robertson, B.A. Bailey, G.W. Simone, F.A. Simone, F.A. Johnson, and W.B. Genung. 1980. Oilseed sunflower research in Florida 1979. Agron. Res. Rep. AG-80–4. March 1980. Inst. of Food and Agric. Sci., Univ. of Florida, Gainesville.

Green, V.E., Jr., W.W. Roath, J.A. Robertson, D.C. Zimmerman, S.M. Yang, and W.B. Genung. 1982. Oilseed sunflower research in Florida 1981. Agron. Res. Rep. AG-82–1. September 1981. Inst. of Food and Agric. Sci., Univ. of Florida.

Green, V.E., Jr., J.A. Robertson, G.W. Simone, R.A. Dunn, W.B. Genung, and S.M. Yang. 1981. Oilseed sunflower research in Florida 1981. Agron. Res. Rep. AG-81–3. May 1981. Inst. of Food and Agric. Sci., Univ. of Florida.

Halvorson, A.D., A.L. Black, J.M. Krupinsky, S.D. Merrill, and D.L. Tanaka. 1999. Sunflower response to tillage and nitrogen fertilization under intensive cropping in a wheat rotation. Agron. J. 91:637–642.

Hardin, B. 1998. Mid-oleic acid sunflower hybrids debut. Agric. Res. 46(6):14–15.

Hu, F.B., J.E. Manson, and W.C. Willett. 2001. Types of dietary fat and risk of coronary heart disease: A critical review. J. Am. Coll. Nutr. 20:5–19.

Izquierdo, N.G., L.A.N. Aguirrezábal, F.H. Andrade, and M.G. Cantarero. 2006. Modeling the response of fatty acid composition to temperature in a traditional sunflower hybrid. Agron. J. 98:451–461.

Jaafar, M.N., L.R. Stone, and D.E. Cordrum. 1993. Rooting depth and dry matter development of sunflower. Agron. J. 85:281–286.

Jing, M., A.R. Folsom, L. Lewis, J.H. Eckfeldt, and J. Ma. 1997. Relation of plasma phospholipid and cholesterol ester fatty acid composition of carotid artery intima-media thickness: The artherosclerosis risk in communities (ARIC) study. Am. J. Clin. Nutr. 65:551–559.

Johnston, A.M., D.L. Tanaka, P.R. Miller, S.A. Brandt, D.C. Nielsen, G.P. Lanfond, and N.R. Riveland. 2002. Oilseed crops for semiarid cropping systems in the northern Great Plains. Agron. J. 94:231–240.

Kleingartner, L.W. 2002. NuSun sunflower oil: Redirection of an industry. p. 135–138. *In* J. Janick and A. Whipkey (ed.) Trends in new crops and new uses. ASHS Press, Alexandria, VA.

Krajcovicova-Kudlackova, M., R. Simoncic, A. Bederova, and J. Klvanova. 1997. Plasma fatty acid profile and alternative nutrition. Ann. Nutr. Metab. 41:365–370.

Lajara, J.R., U. Diaz, and R.D. Quidiello. 1990. Definite influence of location and climatic conditions on the fatty acid composition of sunflower oil. J. Am. Oil Chem. Soc. 67:618–623.

Leon, A.J., F.H. Andrade, and M. Lee. 2003. Genetic analyses of seed-oil concentration across generations and environments in sunflower. Crop Sci. 43:135–140.

Lindstrom, M.J., D.D. Warnes, and S.D. Evans. 1982. A water use comparison between corn and sunflowers. J. Soil Water Conserv. 37:362–364.

Mercau, J.L., V.O. Sadras, E.H. Satorre, C. Messina, C. Balbi, M. Uribelarrea, and A.J. Hall. 2001. On-farm assessment of regional and seasonal variation in sunflower yield in Argentina. Agric. Syst. 67:83–103.

Miller, J.F., and B.A. Vick. 1999. Inheritance of reduced stearic and palmitic acid content in sunflower seed oil. Crop Sci. 39:364–367.

Montgomery, D.C. 2005. Design and analysis of experiments. 6th ed. John Wiley & Sons, New York.

National Agricultural Statistics Service. 2006. Acreage. Agricultural Statistics Board, USDA, 30 June 2006. Available at http://usda.mannlib.cornell.edu/usda/nass/Acre/2000s/2006/Acre-06-30-2006.pdf (accessed June 2007; verified 7 Mar. 2008).

National Sunflower Association. 2007. Available at http://www.sunflowernsa.org (accessed October 2007, verified 7 Mar. 2008).

National Sustainable Agriculture Information Service (NSAIS). 2007. By A. Kurki, A. Hill, and M. Morris. Biodiesel: The Sustainability Dimensions. http://attra.ncat.org/attra-pub/biodiesel_sustainable.html. Accessed June, 2007.

Nielsen, D.C. 1998. Comparison of three alternative oilseed crops for the central Great Plains. J. Prod. Agric. 11:336–341.

Pierson, T.A. 1994. Stearic acid and cardiovascular disease: Questions and answers. Am. J. Clin. Nutr. 60:1017–1072.

Robertson, J.A., J.R. Chapman, and J.R. Wilson. 1978. Relation of days after flowering to chemical composition and physiological maturity. J. Am. Oil Chem. Soc. 55:266–269.

Robinson, R.G. 1978. Production and culture. p. 89–143. *In* J.F. Carter (ed.) Sunflower science and technology. Agron. Monogr. 19. ASA, CSSA, and SSSA, Madison, WI.

Ruiz, R.A., and G.A. Maddonni. 2006. Sunflower seed weight and oil concentration under different post-flowering source-sink ratios. Crop Sci. 46:671–680.

SAS Institute. 1999. SAS OnlineDoc®, Version 8. SAS Inst., Cary, NC.

Schneiter, A.A., and J.F. Miller. 1981. Description of sunflower growth stages. Crop Sci. 21:901–903.

Sobrino, E., A.M. Tarquis, and M.C. Diaz. 2003. Modeling the oleic acid content in sunflower oil. Agron. J. 95:329–334.

Steer, B.T., and G.J. Seiler. 1990. Changes in fatty acid composition of sunflower (*Helianthus annuus*) seeds in response to time of nitrogen application, supply rates and defoliation. J. Sci. Food Agric. 51:11–26.

Stone, L.R., D.E. Goodrum, A.J. Schlegel, M.N. Jaafar, and A.H. Khan. 2002. Water depletion depth of grain sorghum and sunflower in the central high plains. Agron. J. 94:936–943.

U.S. Department of Agriculture, Human Nutrition Information Service. 1992. The food guide pyramid. Home and Garden Bull. 252.

U.S. Department of Agriculture, Soil Survey Division, Natural Resources Conservation Service. 2001. Official soil series descriptions. Available at http://soils.usda.gov/technical/classification/osd/index.html (verified 7 Mar. 2008).

Valchovski, I. 2002. Influence of heavy rate of nitrogen fertilizer on oil content and fatty acid composition of different varieties and hybrids. Rasteniev'dni Nauki 39(5/6):338–341.

Warner, K., B.A. Vick, L. Kleingartner, I. Isaac, and K. Doroff. 2003. Composition of sunflower Nusun, (mid-oleic sunflower) and high-oleic sunflower oils. *In* Proc. Sunflower Res. Workshop, Fargo, ND. 16–17 January. Available at http://www.sunflowernsa.com/research/research-workshop/documents/107.PDF (verified 7 Mar. 2008).